# Scalar Mesons and the Valence Quark Model

J. Vijande, A. Valcarce, F. Fernández

*Grupo de Fısica Nuclear and IUFFyM, Universidad de Salamanca, Salamanca, Spain*

**Abstract.** We link the description of the light scalar mesons to the recently measured open-charm resonances ($D_{sJ}^*(2317)$, $D_{sJ}(2460)$ and $D_0^*(2308)$) by considering them as a mixture of conventional $P-$wave quark-antiquark states and four-quark components.

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An still open puzzle for constituent quark models is the description of the scalar mesons. The most striking problems appeared with the light scalar mesons, their masses do not fit into the quark model predictions in its many variations [1]. The difficulties to identify the recently discovered open-charm resonances with conventional $c\overline{q}$ states are rather similar [2]. These results support the observation that the quark structure of the scalar mesons as probed by the electromagnetic interaction is definitively not consistent with a naive $q\bar{q}$ composition [3].

$q\overline{q}$ states are easily identified with physical hadrons when virtual quark loops are not important. This is the case of pseudoscalar and vector mesons due to the $P-$wave nature of the hadronic dressing. On the contrary, in the scalar sector it is the $q\overline{q}$ pair the one in a $P-$wave state, whereas quark loops may be in a $S-$wave. In this case the intermediate hadronic states may play a crucial role in the composition of the resonance, in other words unquenching may be important.

In nonrelativistic quark models gluon degrees of freedom are frozen and therefore the wave function of a zero baryon number (B=0) hadron may be written as

$$|\mathrm{B}=0\rangle = \Omega_1 \,|q\bar{q}\rangle + \Omega_2 \,|qq\bar{q}\bar{q}\rangle + .... \quad (1)$$

where $q$ denotes quark degrees of freedom and the coefficients $\Omega_i$ accounts for the mixing of two- and four-quark states. $|\mathrm{B}=0\rangle$ systems are then described by a hamiltonian

$$H = H_0 + H_1 \;\text{ being }\; H_0 = \begin{pmatrix} H_{q\bar{q}} & 0 \\ 0 & H_{qq\bar{q}\bar{q}} \end{pmatrix} \; H_1 = \begin{pmatrix} 0 & V_{q\bar{q}\leftrightarrow qq\bar{q}\bar{q}} \\ V_{q\bar{q}\leftrightarrow qq\bar{q}\bar{q}} & 0 \end{pmatrix} . \quad (2)$$

$H_1$, accounting for the mixing between $q\overline{q}$ and $qq\bar{q}\bar{q}$ configurations, can be parametrized by a constant depending on the quark pair annihilated, i.e., $V_{q\bar{q}\leftrightarrow qq\bar{q}\bar{q}} = \gamma$. If this coupling is weak enough one can solve independently the eigenproblem for $H_{q\overline{q}}$ and $H_{qq\bar{q}\bar{q}}$, treating $H_1$ perturbatively. The calculations have been done within the constituent quark model of Ref. [4]. The two-body problem has been solved exactly by means of the Numerov algorithm and the four-body problem by means of a variational method using a combination of generalized gaussians as trial wave function.

The mass and flavor dominant component obtained for the low-lying light-scalar two- and four-quark states are shown in Table 1, compared to the possible experimental as-

**TABLE 1.** Mass (QM), in MeV, and flavor dominant component (Flavor) of the light scalar mesons considered as $q\bar{q}$ or $qq\bar{q}\bar{q}$ states. I stands for the isospin. $nL$ denotes the radial excitation and the orbital angular momentum.

| I | $q\bar{q}$ | | | $qq\bar{q}\bar{q}$ | | Experiment | |
|---|---|---|---|---|---|---|---|
| | $nL$ | QM | Flavor | QM | Flavor | State | Mass |
| 1 | $1P$ | 984 | $(n\bar{n})$ | 1308 | $(nn\bar{n}\bar{n})$ | $a_0(980)$ | 984.7±1.2 |
| | $2P$ | 1587 | $(n\bar{n})$ | 1522 | $(ns\bar{n}\bar{s})$ | $a_0(1450)$ | 1474±19 |
| 0 | $1P$ | 413 | $(n\bar{n})$ | – | – | $f_0(600)$ | 400−1200 |
| | – | – | – | 949 | $(nn\bar{n}\bar{n})$ | $f_0(980)$ | 980±10 |
| | $1P$ | 1340 | $(s\bar{s})$ | – | – | $f_0(1200-1600)$ | 1400±200 |
| | $2P$ | 1395 | $(n\bar{n})$ | – | – | $f_0(1370)$ | 1200−1500 |
| | – | – | – | 1525 | $(ns\bar{n}\bar{s})$ | $f_0(1500)$ | 1507±5 |
| | $3P$ | 1754 | $(n\bar{n})$ | – | – | $f_0(1710)$ | 1714±5 |
| | – | – | – | – | – | $f_0(1790)$ | $1790^{+40}_{-30}$ |
| | $2P$ | 1894 | $(s\bar{s})$ | – | – | $f_0(2020)$ | 1992±16 |
| | – | – | – | 1915 | $(ss\bar{s}\bar{s})$ | $f_0(2100)$ | 2103±17 |
| | $3P$ | 2212 | $(s\bar{s})$ | – | – | $f_0(2200)$ | 2197±17 |
| 1/2 | $1P$ | 1213 | $(n\bar{s})$ | – | – | $K_0^*(800)$ | $\approx$ 800 |
| | $2P$ | 1768 | $(n\bar{s})$ | 1295 | $(nn\bar{n}\bar{s})$ | $K_0^*(1430)$ | 1412±6 |
| | $3P$ | 2046 | $(n\bar{s})$ | 1802 | $(ns\bar{s}\bar{s})$ | $K_0^*(1950)$ | 1945±22 |

signment. As can be seen, for the isoscalar mesons the four-quark states appear precisely in the energy region where no $q\bar{q}$ states are predicted. In spite of that, neither the $q\bar{q}$ nor the $qq\bar{q}\bar{q}$ configurations match the experimental data. When the mixing between two- and four-quark components is considered, Table 2, an almost one-to-one correspondence between theoretical states and experiment is predicted [5]. A dominant four-quark component is found for the $f_0(980)$ (82%), $f_0(1500)$ (72%), $a_0(1450)$(90%)

**TABLE 2.** Mass (QM), in MeV, and flavor dominant component (Flavor) of the light isoscalar, isovector and I=1/2 mesons, mixing two- and four-quark states as explained in the text.

| I=0 | | |
|---|---|---|
| QM | Flavor | Mass |
| 568 | $(n\bar{n})$ | 400−1200 |
| 999 | $(nn\bar{n}\bar{n})$ | 980±10 |
| 1301 | $(s\bar{s})$ | 1400±200 |
| 1465 | $(n\bar{n})$ | 1200−1500 |
| 1614 | $(ns\bar{n}\bar{s})$ | 1507±5 |
| – | – | 1714±5 |
| 1782 | $(n\bar{n})$ | $1790^{+40}_{-30}$ |
| 1900 | $(s\bar{s})$ | 1992±16 |
| 1944 | $(ss\bar{s}\bar{s})$ | 2103±17 |
| 2224 | $(s\bar{s})$ | 2197±17 |

| I=1 | | |
|---|---|---|
| QM | Flavor | Mass |
| 985 | $(n\bar{n})$ | 984.7±1.2 |
| 1381 | $(nn\bar{n}\bar{n})$ | 1474±19 |
| 1530 | $(ns\bar{n}\bar{s})$ | |
| 1640 | $(n\bar{n})$ | – |
| 1868 | $(n\bar{n})$ | – |

| I=1/2 | | |
|---|---|---|
| QM | Flavor | Mass |
| 1113 | $(n\bar{s})$ | $\approx$ 800 |
| 1440 | $(nn\bar{n}\bar{s})$ | 1412±6 |
| 1784 | $(n\bar{s})$ | 1945±20 |
| 1831 | $(ns\bar{s}\bar{s})$ | |
| 2060 | $(n\bar{s})$ | |

**TABLE 3.** Probability (P), in %, of the wave function components and mass (QM), in MeV, of open-charm mesons considering the mixing between $q\bar{q}$ and $qq\bar{q}\bar{q}$. Exp. stands for the experimental data.

| $I=0$ | | | | | | $I=1/2$ | |
|---|---|---|---|---|---|---|---|
| $J^P=0^+$ | | $J^P=1^+$ | | | | $J^P=0^+$ | |
| QM<br>Exp. | 2339<br>2317.4±0.9 | QM<br>Exp. | 2421<br>2459.3±1.3 | 2555<br>2535.3±0.6 | | QM<br>Exp. | 2241<br>2308±17±15±28 |
| P($cn\bar{s}\bar{n}$) | 28 | P($cn\bar{s}\bar{n}$) | 25 | $\sim 1$ | | P($cn\bar{n}\bar{n}$) | 46 |
| P($c\bar{s}_{1^3P}$) | 71 | P($c\bar{s}_{1^1P}$) | 74 | $\sim 1$ | | P($c\bar{n}_{1P}$) | 53 |
| P($c\bar{s}_{2^3P}$) | $\sim 1$ | P($c\bar{s}_{1^3P}$) | $\sim 1$ | 98 | | P($c\bar{n}_{2P}$) | $\sim 1$ |

and the $K_0^*(1430)$ (53%), and an important four-quark component is predicted for the $a_0(980)(21\%)$, although it has a dominant $q\bar{q}$ structure. The final physical picture arising shows an involved structure for the flavor wave function, in agreement with the complicated pattern decays.

In the case of the open-charm mesons, they are easily identified with standard $c\bar{q}$ states except for the cases of the $D_{sJ}^*(2317)$, the $D_{sJ}(2460)$, and the $D_0^*(2308)$ [5]. This is a common behavior of almost all quark potential model calculations [6]. The results obtained for the $cn\bar{s}\bar{n}$ configuration are 2731 and 2699 MeV for $J^P=0^+$ with $I=0$ and $I=1$, and 2841 and 2793 MeV for $J^P=1^+$ with $I=0$ and $I=1$. For the $cn\bar{n}\bar{n}$ configuration with $I=1/2$ the energy is 2505 MeV. The $I=1$ and $I=0$ states are far above the corresponding strong decaying thresholds and therefore should be broad, what rules out a pure four-quark interpretation of the new open-charm mesons. In the isoscalar sector, the $cn\bar{s}\bar{n}$ and $c\bar{s}$ states get mixed, as it happens with $cn\bar{n}\bar{n}$ and $c\bar{n}$ for the $I=1/2$ case.

Once the mixing is considered the $D_0^*(2308)$ presents 46% of four-quark component and 53% of $c\bar{n}$ pair. It is above the isospin preserving threshold $D\pi$, being broad as observed experimentally. The mixed configuration compares much better with the experimental data than the pure $c\bar{n}$ state.

In the strange sector, the $D_{sJ}^*(2317)$ and $D_{sJ}(2460)$ are dominantly $c\bar{s}$ $J=0^+$ and $J=1^+$ states, respectively, with almost 30% of four-quark component. Such component is responsible for the shift of the mass of the unmixed states to the experimental values below the $DK$ and $D^*K$ thresholds. Being both states below their isospin-preserving two-meson threshold, the only allowed strong decay to $D_s^*\pi$ would violate isospin and are expected to have small widths $O(10)$ keV. The second isoscalar $J^P=1^+$ state, with an energy of 2555 MeV and 98% of $c\bar{s}$ component, corresponds to the $D_{s1}(2536)$.

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